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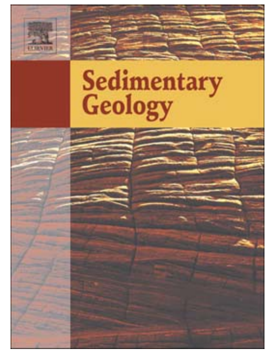

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The potential of detrital garnet as a provenance proxy in the Central Swiss Alps

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Abstract

Detrital garnet is a promising candidate to reliably fingerprint sediment sources in the Alps, which has so far been complicated by the wide range and similarity of some of the lithologies. Garnet is present in most Alpine sediments, is easy to identify, is fairly stable and, most importantly, reflects the type and the metamorphic grade of its source rock in its chemical composition. This study aims to establish fingerprints based on detrital garnet composition for the most important tectonic units of the Central Alps, including European, Penninic and Adriatic basement rocks and their respective metasedimentary covers. Sediments collected from modern rivers, which drain representative portions of the individual tectonic units, contain a natural mixture of the various garnet populations present in each unit. We selected six catchments in southwestern Switzerland draining the External Massifs, Helvetic sediments and the Penninic nappe stack at the transition of Alpine greenschist- to amphibolite-facies metamorphism in order to test the variability of Alpine garnets and the role of inherited (pre-Alpine) garnets. Extraordinary grossular- and spessartine-rich garnets of the External massifs, which experienced greenschist facies metamorphism, are clearly distinguishable from generally almandine-rich garnets supplied by the higher-grade metamorphic Penninic nappe stack. The variable pyrope, grossular and spessartine components of these almandine-rich garnets can be used to further distinguish pre-Alpine, Alpine eclogite-facies and low-grade metasedimentary garnets. This fingerprint has the potential to be used for reconstructing sediment sources, transport and dispersal patterns in a variety of settings throughout the Alpine sedimentary record.

Keywords

Garnet; Central Alps; Provenance; Heavy minerals; Geochemistry; External massifs

1. Introduction

The European Alps were formed as a result of the convergence between the European and the Adriatic continent plates (Trümpy, 1960; Frisch, 1979; Schmid et al., 1996). Ongoing subduction and closure of two marine basins, the Piedmont-Liguria ocean and the Valais trough, resulted in continental collision that gradually incorporated the European continental margin into the orogen. Ever since the first collisional stage in late Cretaceous times (Lihou and Allen, 1996), the Alps have been one of the most important sediment sources in central and southern Europe (e.g., Kuhlemann et al., 2002). Alpine sediments have been either incorporated into the orogenesis from Cretaceous to Oligocene times (flysch), deposited in the foreland basins between the Oligocene and the Miocene (Molasse) or have been transported out of the orogen by fluvial and glacial processes since Miocene times (Allen et al., 1985; Graf, 1993; Schlunegger et al., 1993; Winkler, 1996; Hagedorn and Boenigk, 2008; Garzanti et al., 2011; Reiter et al., 2015).

In order to understand the sources, transport and dispersal patterns of Alpine-derived sediments throughout this geological record, it is important to have fingerprinting tools available which allow to reliably trace the material back to its source. However, the large variability of lithologies within the Alps, and their similarity to rocks outside of the Alps considerably complicates the fingerprinting. Detrital garnet is a promising candidate to address this problem, because its composition varies significantly depending on the chemistry and metamorphic grade of the source rock (Spear, 1994). Garnet geochemistry has been proven suitable to distinguish different source rocks in a variety of settings (Morton, 1985; Teraoka et al., 1998; Sabeen et al., 2002; Morton et al., 2004; Krippner et al., 2014; Andò et al., 2014, Alizai et al. 2016, Krippner et al., 2016). Furthermore, it is relatively common in most Alpine-derived sediments (Füchtbauer, 1964; Garzanti and Andò, 2007, Garzanti et al., 2012), easy to identify and fairly stable during sediment transport and particularly during diagenesis (Morton and Hallsworth, 2007; Andò et al., 2012; Garzanti et al., 2015).

The aim of this study is to understand the overall compositional variety of garnet grains supplied by the major source rocks exposed in the Central Swiss Alps. Several authors have investigated garnet compositions from individual litho-tectonic units and outcrops, which provide valuable petrological details for the bedrocks, but rarely information representative enough for provenance studies.

We therefore complement existing data with analyses on garnets extracted from modern fluvial sediment of selected river catchments.

2. Geological setting

The investigated part of the Central Alps comprises the following main units (Fig. 1): The External massifs, the Helvetic nappes, the Penninic nappes and the Dent Blanche/Sesia zone (Federal Office of Topography Swisstopo, 2011).

The External massifs (Fig. 1) are made up from European continental crust, which was exhumed from deeper crustal levels during the Miocene (e.g., Michalski and Soom, 1990). In the Central Alps, these are the Mont-Blanc, the Aiguilles-Rouges and the Aar massifs (e.g., von Raumer et al., 1999). The External massifs comprise mostly polycyclic basement gneisses with intercalations of amphibolites intruded by Variscan and post-Variscan granites (Berger et al., 2016). Locally, their Carboniferous to Mesozoic metasedimentary cover is preserved as well. The basement units underwent polycyclic metamorphism at different times during the Paleozoic (von Raumer et al., 1999). In addition, all units underwent lower to upper greenschist facies metamorphism during the Tertiary (Frey and Ferreiro Mählmann, 1999; Bousquet et al., 2012;) (Fig. 2).

The Helvetic nappes represent the sedimentary cover of the European passive continental margin, which comprises basically a carbonate shelf sequence of Jurassic, Cretaceous and Eocene age (Pfiffner, 1993, 2015). During Alpine metamorphism, temperature and pressure conditions in these nappes never exceeded 300°C and 2-3 kbar, respectively (Frey and Ferreiro Mählmann, 1999).

The Penninic nappes include three paleogeographic units: The Valais trough (lower Penninic), the Briançonnais swell (middle Penninic), and the Piedmont-Liguria ocean (upper Penninic).

The lower Penninic consists mostly of calcschists and flysch sediments deposited in the Valais trough during the Cretaceous with an Alpine greenschist- and blueschist-facies overprint (Schmid et al., 2004; Bousquet et al., 2012).

The middle Penninic units were part of the Briançonnais swell, a non-continuous eastern spur of the Iberian plate separating the Valais trough in the North from the Piedmont-Liguria ocean in the South (Schmid et al., 2004). This unit comprises Paleozoic metagranitoids, gneisses and schists of the Briançonnais basement as well as their metasedimentary Permian and Mesozoic cover. The Alpine metamorphic overprint of the middle Penninic units increases towards the South, ranging from lower greenschist-facies conditions in the more external Zone Houillère, Pontis and Siviez-Mischabel nappes to blueschist-facies conditions in the more internal Mont Fort, Cimes Blanches and Frilihorn nappes (Desmons et al., 1999; Bousquet et al., 2012) (Fig. 2). Parts of the middle Penninic basement units, however, preserve amphibolite to eclogite-facies metamorphism of pre-Alpine age (Thélin et al., 1990; Sartori et al., 2006;). The upper Penninic contains calcschists and an ophiolite complex including metabasalts, metagabbros and serpentinites that were formed in response to Jurassic and Cretaceous ocean floor spreading in the Piedmont-Liguria ocean (Schmid et al., 2004). These units underwent

Alpine eclogite-facies metamorphism (Frey et al., 1999; Bucher et al., 2005).

The Gotthard nappe and the Lepontine dome are large fragments of European continental crust, but because of their structural position below the Penninic nappe stack ("sub-penninic") they are considered as allochthonous nappes rather than autochthonous massifs (Schmid et al., 2004). These units comprise gneisses and granitoid rocks, as well as some minor Mesozoic metasedimentary cover. During Alpine metamorphism, the Gotthard nappe underwent upper greenschist-facies conditions similar to the External massifs, whereas the Lepontine nappes experienced amphibolite facies conditions (Todd and Engi, 1997; Frey et al., 1999; Berger et al., 2011; Bousquet et al., 2012;) (Fig. 2). The Dent Blanche nappe, which is a tectonic sliver of Adriatic provenance, was thrusted onto the upper Penninic unit (Dal Piaz, 1999). It comprises Paleozoic polymetamorphic metagranitoids and gneisses that experienced an Alpine overprint of blueschist-facies conditions.

In summary, the Alpine metamorphic grade increases from North to South (Fig. 2). One important border is the Rhône-Simplon lineament that separates the mostly greenschist-facies European units in the Northwest from the higher-grade Penninic units in the Southeast (Mancktelow, 1985).

Geomorphologically, the region is characterized by some of the highest Alpine mountain peaks such as the Mont Blanc and the Monte Rosa massif, high topographic gradients, orographic rainfall and significant glacial cover in the higher regions (Frei and Schär, 1998; Kühni and Pfiffner, 2001; Stutenbecker et al., 2016). Accordingly, water and sediment supply feeding for example the headwaters of the Rhône and Rhine rivers (Fig. 1) depend strongly on seasonal snow and ice melting processes (Costa et al., 2017). Overall, erosion rates in this part of the Alps are amongst the highest measured rates in Europe (Wittmann et al., 2007, Norton et al., 2010).

3. Methods

We sampled modern fluvial sediment at the outlet of selected river catchments that ideally drain only one of the currently exposed litho-tectonic units. Because the collected fluvial sediment at the outlet of the target basin is likely to contain a representative mixture of material from the bedrock farther upstream, we anticipate that this approach will average out spatial clustering of garnets in the bedrock (e.g., von Blanckenburg, 2005, for a similar issue related to in-situ cosmogenic nuclide analysis). We chose six river catchments including from west to east the Trient river draining the Aiguilles-Rouges and partly the Mont-Blanc massif, the Morge river draining the Helvetic nappes, the Borgne and Vispa rivers draining the Penninic nappes and parts of the Dent Blanche complex, the Wysswasser river sourced in the Aar massif and the Goneri river derived from the Gotthard nappe. These particular rivers were chosen because of their accessibility on the one hand, and on the other hand because their catchment areas are large enough (>40 km^2) to drain a representative numbers of lithologies.

One sand sample per catchment was taken as close to the outlet of the river as possible. The samples were wet-sieved, and the fraction 63-250 μm was processed with the heavy liquid lithium heteropolytungstate (LST, 2.85 g/cm^3). The obtained heavy mineral concentrate was micro-split, and all garnets were hand-picked from this fraction. Like this, between 36 and 105 garnets were selected, mounted on grain mounts and polished. A summary of the sample characteristics is given in Table 1.

Energy-dispersive X-ray spectroscopy (EDS) analysis was carried out at the University of Bern using a ZeissEvo®50 scanning electron microscope. Data were measured using an accelerating voltage of 20kV and a beam current of 2 nA. Element quantification was performed using the EDAX TEAM software (Nylese and Anderhalt, 2014) using standardless ZAF correction. The data were cross-checked by wavelength dispersive X-ray spectroscopy (WDS) data of selected garnet grains using a JEOL JXA-8200 electron probe micro-analyser at the University of Bern. These data were measured using 15 kV, 15 nA and natural and synthetic standards. Detection limits, standards used and a comparison of the EDS and WDS data are provided in the supplementary material.

From the measured oxide compositions molecular proportions were calculated on the base of 12 oxygens. Garnet-endmember proportions were calculated using the Microsoft Excel spreadsheet developed by Locock (2008). The measured garnets can be described in the compositional space of almandine-pyrope-spessartine-grossular. Other fractions (e.g., andradite) are only minor and thus negligible for this study. Chemical compositions (in wt%) of all detrital garnet grains are provided in the supplementary material. In order to be able to compare the detrital garnet data with source rock compositions, we assembled a database with all available garnet compositions published in the studied area (Fig. 1). The garnets were organized according to their bedrock lithology and thus grouped into (1) Variscan granitic intrusions from the External massifs ("Zentraler Aaregranit", Rotondo and Mont Blanc granite), (2) polycyclic basement of the External massifs (3), crystalline basement of the Austroalpine Dent Blanche complex, (4) crystalline basement of the middle Penninic Briançonnais units (mostly Siviez-Mischabel nappe), (5) metasedimentary cover of the Dent-Blanche complex, (6) metasedimentary cover of the middle Penninic Briançonnais units (7) eclogites (mostly meta-basalts) of the upper Penninic Zermatt-Saas Fee zone and the middle Penninic basement.

Depending on the studied rocks and the aim of the research, several ternary plots have been proposed for plotting garnet compositions (Teraoka et al., 1997; Mange and Morton, 2007; Aubrecht et al., 2009; Suggate and Hall, 2013; Krippner et al., 2014). Here, we chose a combined triple ternary plot, which displays spessartine, grossular and pyrope in the first diagram (following Teraoka et al., 1997, 1998), almandine, grossular and pyrope contents in the second one, and almandine, grossular and spessartine in the third one (following Aubrecht et al., 2009).

4. Results and provenance interpretation

4.1 Source rock data

The minimum, maximum and mean values of garnet compositions collected from the literature are summarized in Table 2. Garnet compositions of the source rocks plotted in the triple ternary plot are displayed in Fig. 3 for the External massifs and Fig. 4 for the Penninic nappes and Dent Blanche unit.

For the External massifs, the two populations of garnets derived from Variscan intrusions and the polycyclic basement are well distinguishable in the triple ternary plot (Fig. 3). The Variscan granite garnets are rich in grossular and spessartine, which together make up 69-84 % of the garnet composition. The content of almandine is only minor with 15-30 %, whereas pyrope contents are very low (~1%). In manganese-poor rocks such as the Variscan granites (<0.1 wt%, Steck and Burri, 1971), the manganese-rich spessartine often grows first during metamorphism (Spear, 1994).

Garnets derived from the polycyclic basement are generally rich in almandine (38-77%) with varying contents of pyrope, grossular and spessartine (Table 2). Their wide scatter can be explained by the complex polycyclic history of these rocks, which preserved garnets that grew during different metamorphic events (von Raumer et al., 1999). Without further data acquisition, however, it is not possible to further subdivide groups of garnets in this unit.

Garnet compositions from the crystalline basements of the Dent Blanche complex and the middle Penninic Briançonnais units are plotted in Fig. 4a. Similar to the European basement garnets, these garnets are almandine-dominated (34%-84%) with low spessartine components (0-9%) and varying pyrope and grossular contents (both 0-30%). Given the small amount of data and the large overlap of both clusters, it is not possible to certainly distinguish garnets derived from the Dent Blanche basement rocks from the middle Penninic ones. However, the available data suggest that garnets from the Dent Blanche crystalline basement are relatively enriched in pyrope (maximum of 30%) in comparison to middle Penninic basement rocks (maximum of 18%). Pyrope contents tend to increase with increasing metamorphic grade (Spear, 1994). The higher pyrope content could be explained by pre-Alpine granulite-facies conditions preserved locally in the Dent-Blanche complex (Gardien et al., 1994) in contrast to the middle Penninic units, which only experienced amphibolite facies metamorphism (Frey et al., 1999). However, more source rock data would be needed to support this interpretation.

Garnets from the meta-sedimentary cover of the Dent Blanche and middle Penninic may reach spessartine contents of up to 55% (Fig. 4b). High spessartine components are typical in garnets grown at lower greenschist facies conditions of ca. 300-375°C and 4-5 kbar in sedimentary rocks (Bucher and Bousquet, 2007). The fact that the metasedimentary cover sequences probably comprise different generations of garnets, including those recycled from the underlying basements, explains the large scatter of data. The almandine component varies widely (10-80%), but is on average lower than in the crystalline basement garnets (Table 2). Grossular contents vary between 4 and 29%, whereas pyrope contents are below 11%. Garnets from the Dent Blanche metasedimentary cover seem to have higher spessartine contents (maximum of 29%) than the ones from the middle Penninic cover (maximum of 14%), but this statement warrants confirmation with additional data.

Garnets from the eclogitic source rocks have the highest observed pyrope contents of up to 45% and significant grossular contents of up to 40% (Table 2). At high temperature and pressure conditions, garnets tend to incorporate magnesium and calcium rather than iron into their crystal lattices, leading to an increase of pyrope- and grossular-contents and a relative depletion in almandine (Wright, 1938; Deer et al., 1992). In particular, grossular-contents may increase in high-pressure metamorphic conditions depending on the bulk rock composition (Spear, 1994). In the ternary plot, 95% of the data plot in a rather narrow cluster with low spessartine components (Fig. 4c). 5% of the data, however, show slightly elevated spessartine-contents. These data are either derived from calcschists that show elevated manganese contents in their bulk geochemistry (Reinecke, 1998) or from within shear zones (Cartwright and Barnicoat, 2002). Their composition is more in agreement with garnets from the metasedimentary covers of the Dent Blanche or middle Penninic units (Fig. 4b). Eclogitic garnets from the upper Penninic Zermatt-Saas Fee zone and the Briançonnais basement are not distinguishable.

4.2 Detrital data

Detrital garnet compositions from the Goneri, Trient and Wysswasser rivers draining the External massifs and the Gotthard nappe are plotted in Fig. 5a.

From all three rivers, around 25% of the data plot within the cluster of the polycyclic basement. Around 50% of the data are in good agreement with the Variscan granite garnets, although the compositional range is wider than suggested from the little literature data available (Fig. 5a, cluster with dashed red line). Another 25% of the data, however, are not in agreement with both clusters. These almandine-rich garnets with very low grossular (<6%) and variable spessartine contents can be best distinguished in the pyrope-spessartine-grossular plot (Fig. 5a, cluster with dashed yellow line). This composition is generally indicative of garnets formed in sedimentary rocks during low-grade metamorphism (Spear, 1994). The fact that they are especially abundant in the Trient catchment, which comprises a significant amount of Carboniferous to Cretaceous metasedimentary cover, would support this interpretation (Fig. 6). In the Goneri and Wysswasser catchments the amount of sedimentary cover is only minor, and this composition is found less frequently.

Garnets found in the Borgne and Vispa sediments plot mostly in the clusters of crystalline basement rocks and eclogites (Fig. 5b). Since these two clusters overlap quite significantly, it is not possible to identify the origin of each single grain. However, the different almandine contents of eclogite and crystalline basement garnets (best seen in the middle grossular-pyrope-almandine plot, Fig. 5b) provide some possibility to distinguish them from each other. Garnets with very high almandine contents (>68%) can be assigned to the crystalline basement with high probability. Following this approach, at least 20% of the Borgne garnets and at least 48% of the Vispa garnets can be interpreted to have been derived from crystalline basement rocks. Due to their very high spessartine components (>15%), which can be best seen in the right almandine-grossular-spessartine plot in Fig. 5b, 25% of the Borgne garnets and 3% of the Vispa garnets can certainly be classified as being derived from metasedimentary cover units. This is in good agreement with the higher amount of metasedimentary cover rocks in the Borgne catchment (Fig. 6). The remaining ~50% of grains cannot be definitely classified based on their composition.

The provenance of garnets found in the Morge river sample (Fig. 5c) is much more difficult to determine, since garnet has never been reported from any lithologies within the Helvetic nappes and source rock compositions are not available. During Alpine metamorphism, however, temperature and pressure conditions in the Helvetic nappes never exceeded 300°C and 2-3 kbar, respectively, making the presence of Alpine garnet impossible (Frey and Ferreiro Mählmann, 1999). Platform carbonates are the clearly dominating lithology within the Helvetic nappes, and their detrital heavy mineral concentration is generally very low (see Table 1). However, some siliciclastic rocks are present as well. These are mostly thin intercalated mud- and siltstones, as well as calcareous sandstones (Cardello, 2013; Pfiffner, 2015). Few detrital garnets from these minor siliciclastic rocks could be relatively enriched in the heavy mineral suite of the fluvial sediment. In this case, the garnets must have been eroded from the European basement in Mesozoic times and should accordingly show similar compositions to the basement garnets found in the Wysswasser, Trient or Goneri samples. Alternatively, Tertiary sediments cropping out in the North of the Morge catchment (Fig. 6) could as well contain Paleocene to Oligocene Penninic material. In other locations, these Paleogene Helvetic sediments were shown to be at least partially transported by north-directed paleocurrents. Accordingly, they could comprise material eroded from the Penninic units in the South (Hsu, 1960; Siegenthaler, 1974). Unfortunately, the compositions of the Morge garnets are rather ambiguous (Fig. 5c). The similarity of basement rocks from the Dent Blanche, middle Penninic and European basement is well illustrated in this example, and it is thus impossible to unambiguously determine the provenance of these garnets.

5. Discussion

This study analysed the variation of garnet geochemistry amongst different source rock groups in the Central Alps. Although most garnets in the study area are generally almandine-dominated with varying grossular, spessartine and pyrope contents, we were able to identify some compositional trends and threshold values that may be used to further distinguish garnets derived from crystalline basement, metasedimentary and eclogitic source rocks (Table 2). Additionally, the triple ternary plot we used in this study can be of visual help, as it illustrates for example the fine differences in pyrope, spessartine and grossular contents in generally almandine-dominated garnets. However, the provenance of garnets, whose compositions plot in the interface of two or three clusters cannot be determined properly. Additional data might help to further distinguish for example the various polycyclic crystalline basement rocks (Dent Blanche, middle Penninic, External massifs) with more detail or Alpine eclogitic garnets from Paleozoic ones.

By analysing detrital garnets in rivers located in the Central Swiss Alps, we found that grossular-spessartine-rich varieties supplied by the European External massifs can be found relatively frequent in the modern fluvial sediment. These garnets, although hardly described in the literature, provide an excellent provenance proxy due to their significantly different compositions from garnets supplied by Penninic or Dent Blanche sources. Furthermore, the geochemical data of detrital material derived from the Trient, Wysswasser and Goneri rivers revealed an additional variety of garnet supplied by the External massifs, which so far was not reported from any source rock in this unit (Fig. 5a, cluster with dashed yellow line). These almandine-rich (51-79%) garnets with very low grossular (<6%), varying spessartine (2-38%) and pyrope (3-25%) contents are probably of metasedimentary origin. Further investigation about their origin is needed to evaluate their possible application in provenance studies.

6. Conclusions

Garnet geochemistry can be used to complement the understanding of sediment sources and fluxes throughout Alpine history, especially when combined with other provenance methods (Najman, 2006; Garzanti et al., 2012; Garzanti et al., 2016). Sediments post-dating Alpine metamorphism with sources located in the External massifs that experienced greenschist metamorphic conditions will likely contain detrital grossular-spessartine-rich garnets. The compositional difference to the generally almandine-rich garnets from Penninic and Austroalpine sources might be of valuable help for provenance analysis in the younger Alpine history, for example in the reconstruction of glacial extents (Gasser and Nabholz, 1969) or Pleistocene fluvial drainage patterns (Tebbens et al., 1995; Hagedorn and Boenigk, 2008; Hoselmann, 2008; Reiter et al., 2015).

Sediments deposited before the Tertiary Alpine metamorphic peak will not contain those grossular-spessartine rich garnets. We demonstrated this for the case of the Morge catchment, where the provenance of detrital grains could not be determined due to the similarity of the possible source rock garnets. However, the ratio of metasedimentary to basement garnets might be used in those and similar deposits to better understand exhumation or unroofing trends (Wildi et al., 1985; Winkler et al., 1985; von Eynatten, 2003; Najman, 2006; Garzanti et al., 2007).

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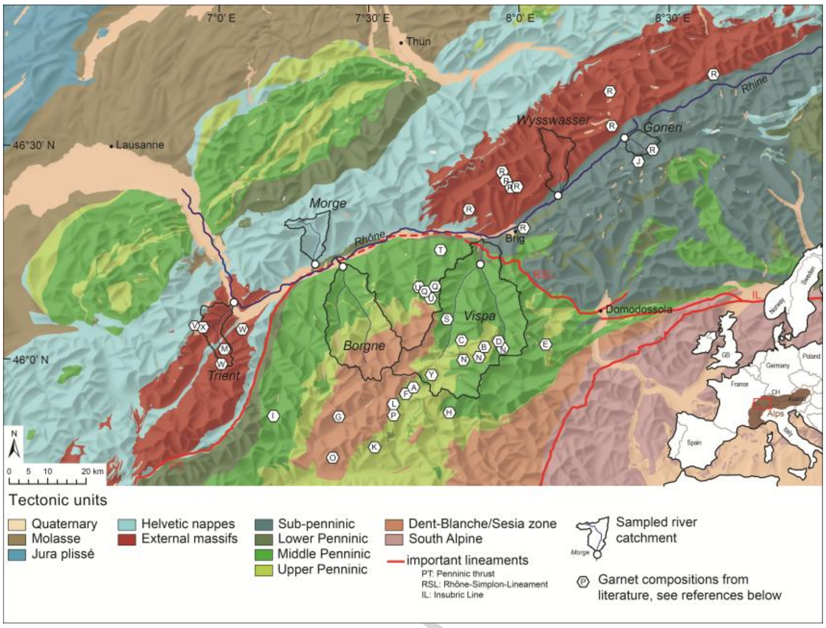
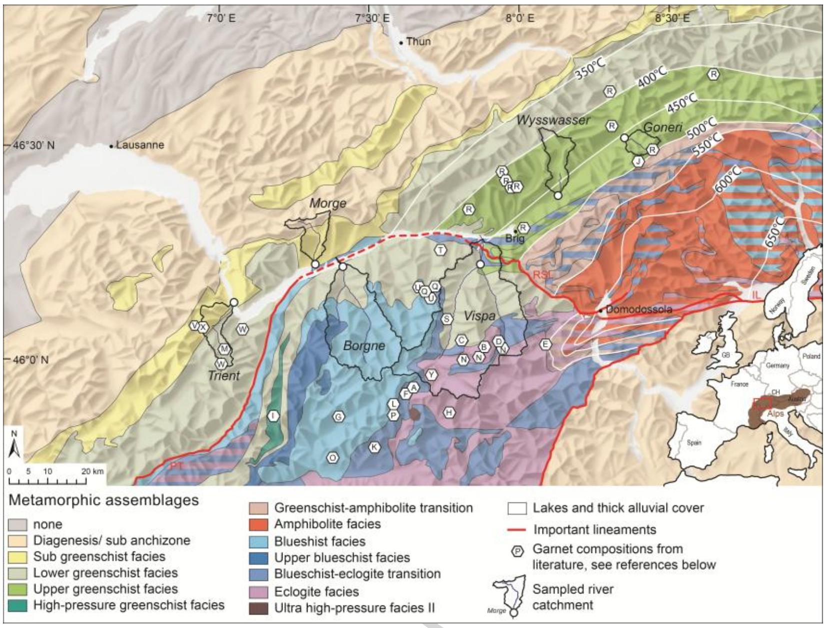

7°0' E
7°30' E
8°0' E
8°30' E
Thun
Lausanne
46°30' N
46°0' N
Morge
Rhône
Wysswasser
Goneri
Rhine
Brig
RSL
Domodossola
IL
Borgne
Vispa
Trient
N
0 5 10 20 km
Tectonic units
Quaternary
Molasse
Jura plissé
Helvetic nappes
External massifs
Sub-penninic
Lower Penninic
Middle Penninic
Upper Penninic
Dent-Blanche/Sesia zone
South Alpine
important lineaments
PT: Penninic thrust
RSL: Rhône-Simplon-Lineament
IL: Insubric Line
Sampled river catchment
Morge
Garnet compositions from literature, see references below
France
Spain
Germany
Poland
CH
Austria
Alps
Italy

Figure 1


7°0' E
7°30' E
8°0' E
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Thun
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Lausanne
46°0' N
350°C
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450°C
500°C
550°C
600°C
650°C
Wysswasser
Gonen
Morge
Brig
RSL
Domodossola
IL
Vispa
Borgne
Trient
PT
N
0 5 10 20 km
Metamorphic assemblages
none
Diagenesis/ sub anchizone
Sub greenschist facies
Lower greenschist facies
Upper greenschist facies
High-pressure greenschist facies
Greenschist-amphibolite transition
Amphibolite facies
Blueshist facies
Upper blueschist facies
Blueschist-eclogite transition
Eclogite facies
Ultra high-pressure facies II
Lakes and thick alluvial cover
Important lineaments
Garnet compositions from literature, see references below
Sampled river catchment

Figure 2

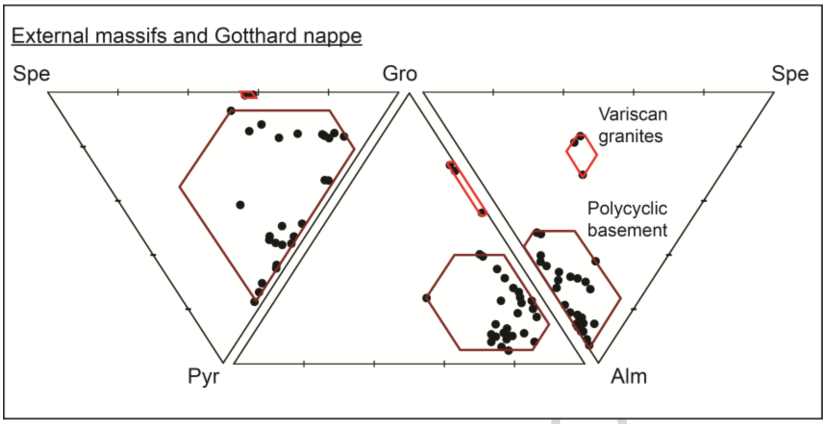

External massifs and Gotthard nappe
Spe
Gro
Spe
Variscan granites
Polycyclic basement
Pyr
Alm

Figure 3

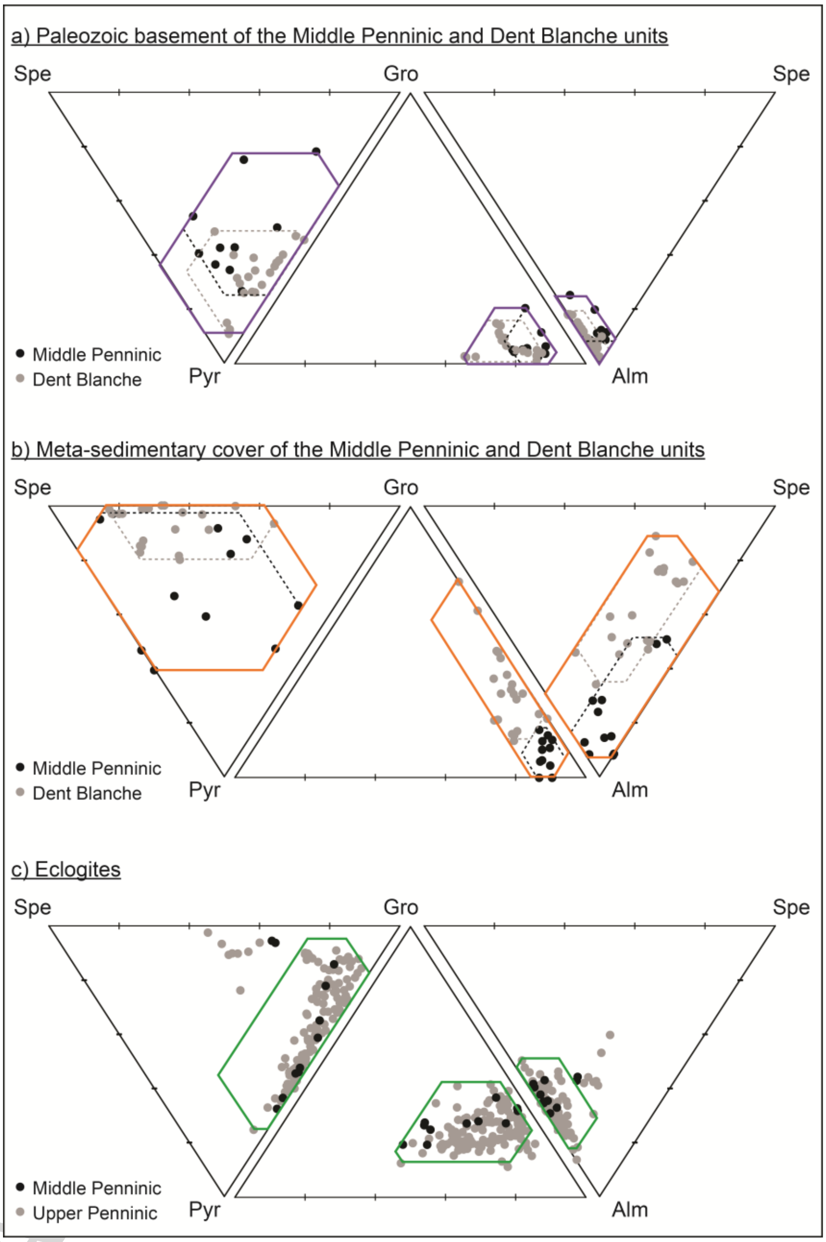

a) Paleozoic basement of the Middle Penninic and Dent Blanche units
Spe
Gro
Spe
Middle Penninic
Dent Blanche
Pyr
Alm
b) Meta-sedimentary cover of the Middle Penninic and Dent Blanche units
Spe
Gro
Spe
Middle Penninic
Dent Blanche
Pyr
Alm
c) Eclogites
Spe
Gro
Spe
Middle Penninic
Upper Penninic
Pyr
Alm

Figure 4

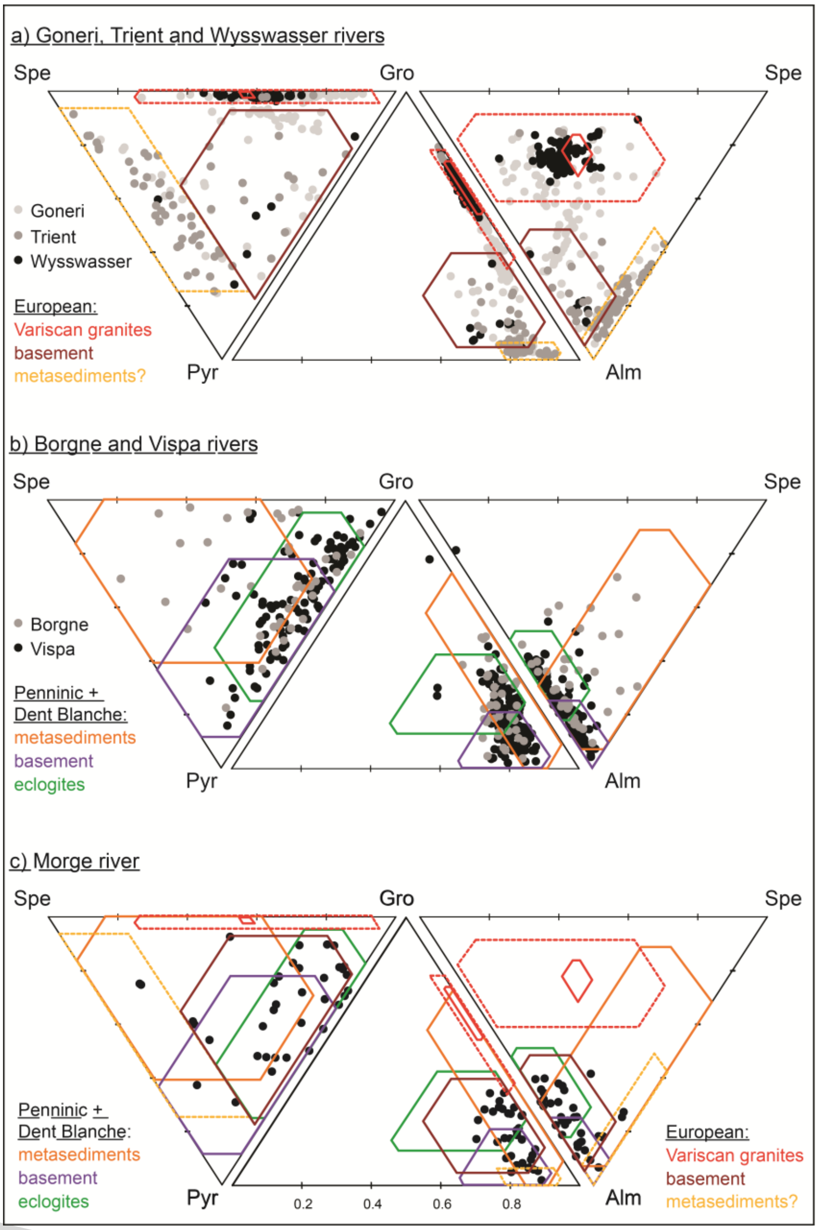
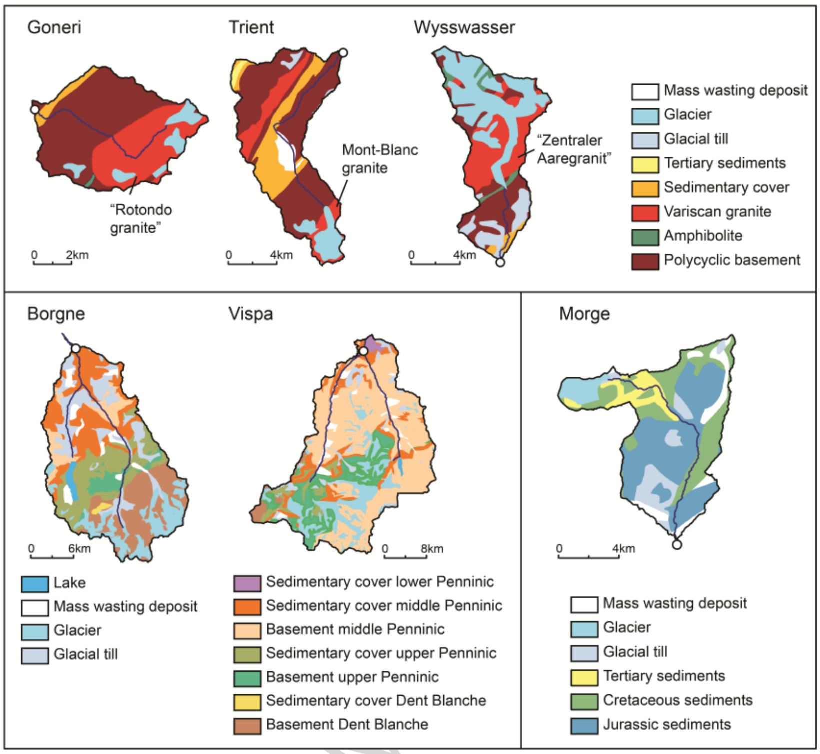

a) Goneri, Trient and Wysswasser rivers
Spe
Gro
Spe
Goneri
Trient
Wysswasser
European:
Variscan granites
basement
metasediments?
Pyr
Alm
b) Borgne and Vispa rivers
Spe
Gro
Spe
Borgne
Vispa
Penninic +
Dent Blanche:
metasediments
basement
eclogites
Pyr
Alm
c) Morge river
Spe
Gro
Spe
Penninic +
Dent Blanche:
metasediments
basement
eclogites
Pyr
0.2
0.4
0.6
0.8
Alm
European:
Variscan granites
basement
metasediments?

Figure 5



Goneri
Trient
Wysswasser
"Rotondo granite"
Mont-Blanc granite
"Zentraler Aaregranit"
0 2km
0 4km
0 4km
Mass wasting deposit
Glacier
Glacial till
Tertiary sediments
Sedimentary cover
Variscan granite
Amphibolite
Polycyclic basement
Borgne
Vispa
Morge
0 6km
0 8km
0 4km
Lake
Mass wasting deposit
Glacier
Glacial till
Sedimentary cover lower Penninic
Sedimentary cover middle Penninic
Basement middle Penninic
Sedimentary cover upper Penninic
Basement upper Penninic
Sedimentary cover Dent Blanche
Basement Dent Blanche
Mass wasting deposit
Glacier
Glacial till
Tertiary sediments
Cretaceous sediments
Jurassic sediments

Figure 6

Fig. 1: Tectonic map of the Central Swiss Alps, indicating the major tectonic units. Modified after Federal Office of Topography Swisstopo (2011). The six sampled catchments are outlined in black. Garnet compositions from the literature are indicated as white polygons. The letters refer to the following references: A: Angiboust et al. (2009), B: Bucher and Grapes (2009), C: Cartwright and Barnicoat (2002), D: Chinner and Dixon (1973), E: Engi et al. (2001), F: Ernst and Dal Piaz (1978), G : Gardien et al. (1994), H: Gasco et al. (2011), I: Giorgis et al. (1999), J: Kamber (1993), K: Kirst (2014), L: Manzotti et al. (2012), M: Marshall et al. (1997), N: Oberhänsli (1980), O: Pennacchioni and Cesare (1997), P: Reinecke (1998), Q: Sartori (1990), R: Steck and Burri (1971), S: Thélin (1987), T: Thélin and Ayrton (1983), U: Thélin et al. (1990), V: von Raumer et al. (1990), W: von Raumer and Bussy (2004), X: von Raumer and Schwander (1985), Y: Weber and Bucher (2015). Not on map: Bucher and Bousquet (2007).

Fig. 2: Map of the Alpine metamorphism of the Central Swiss Alps. From North to South the metamorphic grade is increasing. Modified after Bousquet et al. (2012).

Fig. 3: Results of garnet analysis for the source rocks of the External massifs. Garnets of the Variscan granites of the Mont Blanc and Aar massif (Steck and Burri, 1971; von Raumer and Bussy, 2004) have higher grossular and spessartine contents in contrast to garnets derived from the polycyclic basement gneisses (von Raumer and Schwander, 1985; von Raumer et al., 1990, Kamber, 1993; Marshall et al., 1997).

Fig. 4: Results of garnet analysis for the source rocks of the Penninic nappes and the Dent Blanche complex. a) Garnet compositions from crystalline basement rocks of the Dent Blanche complex (dashed grey line), the middle Penninic nappes (dashed black line) and both combined (thick purple line). Literature data for the Dent Blanche complex from Gardien et al. (1994), Pennacchioni and Cesare (1997) and for the middle Penninic nappes from Thélin and Ayrton (1983), Thélin (1987), Engi et al. (2001). b) Garnet compositions from metasedimentary cover rocks of the Dent Blanche complex (grey

dashed line), the middle Penninic nappes (black dashed line) and both combined (thick orange line). Literature data for the Dent Blanche from Kirst (2014) and Manzotti et al. (2012), and for the middle Penninic nappes from Giorgis et al. (1999), Bucher and Bousquet (2007) and Gasco et al. (2011). c) Garnet compositions from the eclogite rocks of the upper Penninic Zermatt-Saas Fee zone (Chinner and Dixon, 1973; Ernst and Dal Piaz, 1978; Oberhänsli, 1980; Reinecke,1998; Cartwright and Barnicoat, 2002; Angiboust et al., 2009; Bucher and Grapes, 2009; Weber and Bucher, 2015) and middle Penninic basement (Sartori, 1990; Thélin et al., 1990).

Fig. 5: Results of detrital garnet analysis for samples derived from a) the Goneri, Trient and Wysswasser catchments draining the External massifs and the Gotthard nappe, b) the Borgne and Vispa rivers draining the Penninic nappe stack and parts of the Dent Blanch complex and c) the Morge river draining the Helvetic nappes. The clusters with solid lines refer to the same clusters defined in Fig. 3 and Table 2. Indicated by dashed lines we suggest a wider compositional variability of garnets for the Variscan granites based on the detrital grains and an additional group of garnets possibly derived from metasedimentary rocks. For sample locations see Fig.1.

Fig. 6: Geological maps of the studied catchment showing the main lithologies. See Fig. 1 for locations. Modified from Federal Office of Topography Swisstopo (2011).

Table 1: Summary of the fluvial samples taken. The heavy mineral concentration HM% is calculated following Garzanti and Andò (2007b). Garnet % is the estimated percentage of garnet contained in the heavy mineral fraction. ZTR is the sum of the ultrastable heavy minerals zircon, tourmaline and rutile.

Table 2: Compositional ranges (min-max and mean values) of garnets found in the seven main lithological groups from previous studies conducted in the study area. For location of the literature data see Fig. 1. A: Angiboust et al. (2009), B: Bucher and Grapes (2009), C: Cartwright and Barnicoat (2002), D: Chinner and Dixon (1973), E: Engi et al. (2001), F: Ernst and Dal Piaz (1978), G : Gardien et al.

(1994), H: Gasco et al., (2011), I: Giorgis et al., (1999), J: Kamber (1993), K: Kirst (2014), L: Manzotti et al. (2012), M: Marshall et al. (1997), N: Oberhänsli (1980), O: Pennacchioni and Cesare (1997), P: Reinecke (1998), Q: Sartori (1990), R: Steck and Burri (1971), S: Thélin (1987), T: Thélin and Ayrton (1983), U: Thélin et al. (1990), V: von Raumer et al. (1990), W: von Raumer and Bussy (2004), X: von Raumer and Schwander (1985), Y: Weber and Bucher (2015).

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Sample	Grain size (µm)	Heavy mineral index HM%	Dominant heavy minerals	Garnet %	Number of garnets analysed
Borgne	63-250	12.70 “very rich”	epidote-hornblende	~5	40
Goneri	63-250	2.90 “moderately rich”	hornblende-epidote-garnet	~10	105
Morge	63-250	0.04 “very poor”	epidote-hornblende-apatite-ZTR	~1	36
Trient	63-250	3.06 “moderately rich”	epidote-hornblende-ZTR	~5	57
Vispa	63-250	25.85 “extremely rich”	hornblende-epidote-garnet	~15	100
Wysswasser	63-250	5.74 “rich”	epidote-hornblende	~10	52

Table 2: Compositional ranges (min-max and mean values) of garnets found in the seven main lithological groups from previous studies conducted in the study area. For location of the literature data see Fig. 1. A: Angiboust et al. (2009), B: Bucher and Grapes (2009), C: Cartwright and Barnicoat (2002), D: Chinner and Dixon (1973), E: Engi et al. (2001), F: Ernst and Dal Piaz (1978), G : Gardien et al. (1994), H: Gasco et al., (2011), I: Giorgis et al., (1999), J: Kamber (1993), K: Kirst (2014), L: Manzotti et al. (2012), M: Marshall et al. (1997), N: Oberhänsli (1980), O: Pennacchioni and Cesare (1997), P: Reinecke (1998), Q: Sartori (1990), R: Steck and Burri (1971), S: Thélin (1987), T: Thélin and Ayrton (1983), U: Thélin et al. (1990), V: von Raumer et al. (1990), W: von Raumer and Bussy (2004), X: von Raumer and Schwander (1985), Y: Weber and Bucher (2015).

Unit	Almandine (%)	Pyrope (%)	Spessartine (%)	Grossular (%)	References
Variscan granite (External massifs)	16-30 Ø 21	0-1 Ø1	30-36 Ø 33	39-47 Ø 44	W, R
Polycyclic basement (External massifs)	39-77 Ø 65	3-30 Ø 13	1-18 Ø 4	5-37 Ø 17	J, M, V, X
Polycyclic basement (Dent Blanche)	62-84 Ø 73	9-32 Ø 17	0-5 Ø 2	1-15 Ø 7	G, O
Polycyclic basement (Middle Penninic)	69-84 Ø 76	6-18 Ø 12	1-8 Ø 5	2-20 Ø 7	E, S, T, U
Metasedimentary cover (Dent Blanche)	10-64 Ø 35	0-11 Ø 4	15-55 Ø 40	9-29 Ø 17	L, K
Metasedimentary cover	46-80	1-8	2-42	4-14	H, I, Bucher & Bousquet (2007)

(Middle Penninic)	Ø 69	Ø 6	Ø 14	Ø 7	
Eclogites	36-68	2-45	0-15	12-41	A, B, C, D, F, N, P, Q, U, Y
	Ø 54	Ø 18	Ø 2	Ø 23	